Strain sensitivity of gate leakage in strained-SOI nMOSFETs: A benefit for the performance trade-off and a novel way to extract the strain-induced band offset

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1. Introduction

Strained silicon films have been recently introduced in CMOS technologies to boost mobility performance of metal–oxide–semiconductor field-effect-transistors [1–3]. The modification of the silicon band structure induced by biaxial strain also affects the threshold voltage Vt [4,5] and the gate leakage current density Jg [6–10], which has strong implication on circuit performance by reducing power consumption. Although accurate knowledge of the deformation potential values would be useful for modelling tools, there is still no consensus about their exact values, as shown by the various set of parameters found in the literature [11–13] (see inset of Fig. 3). In this paper, we propose to use the strain sensitivity of gate leakage to give realistic parameters. Results are compared to those obtained from an extraction based on the Vt shift, AVt.

2. Experimental details

Lightly p-doped undoped (Na = 10^{15} at/cm^3) SOI and strained-SOI (sSOI) substrates have been used for this analysis [14]. The sSOI substrates have been fabricated using a relaxed Si1−xGe x starting buffer layer with Ge content of 20%, 30% and 40%. The top Si layers have then been thinned down to 10 nm by sacrificial oxidations. Thanks to this process, sSOI substrates do not suffer from Ge out diffusion towards the gate oxide interface [15,16] since the starting SiGe layer is removed before device processing (Inset of Fig. 1).

The tensile biaxial stress σ induced in the Si films was measured by Raman spectroscopy. It was estimated to 1.3 GPa, 2.0 GPa and 2.5 GPa, corresponding to an in-plane deformation ε// of 0.72%, 1.1% and 1.38%, respectively (Fig. 1). The amount of stress in the SOI film was proportional to the Ge content x, apart from a small relaxation for x = 40%.

nMOSFETs have then been fabricated using a conventional process flow. A 5 nm SiO2 film (t ox) was thermally grown and a n+(10^{19} cm^{-3}) highly-doped poly-silicon film was used as gate electrode. As a consequence, the threshold voltage Vt was negative, as shown in Fig. 2 (Vt = −0.12V for unstrained-SOI devices). The resulting EOT is around 4.8 nm, as determined by fitting C–V measurements to 1D Poisson–Schrödinger simulations. Measurements have been performed on 10 × 10 μm^2 devices.

3. Results and discussions

3.1. Mobility

A 75% and 90% electron mobility (μe) gain at high electrical field (at Ninv = 10^{13} cm^{-2} corresponding to Eeff ~0.78 MV/cm) was obtained for sSOI 20% and 30%, respectively (Fig. 1). Such an increase
3.2. Threshold voltage

Figs. 2 and 3 show that $V_t$ decreases linearly with $\sigma$. Assuming an ideal gate oxide (no interface states and no fixed charges), the threshold voltage in FD-SOI single gate devices can be analytically expressed as [17]:

$$V_t = \phi_M - \chi_{\text{Si}} - \frac{E_{\text{gsi}}}{2} + \frac{k_B T}{q} \ln \left( \frac{C_{ox} k_B T}{q^2 \tau_{\text{ox}} \sigma_{\text{si}}} \right) + \frac{\hbar^2 \pi^2}{8 q m_{\text{si}}^*}$$

(1)

It depends on the temperature $T$, the properties of the Si film (i.e., the electron affinity $\chi_{\text{Si}}$, the silicon bandgap $E_{\text{gsi}}$, the film thickness $t_{\text{si}}$ and the intrinsic carrier concentration $n_{\text{si}}^0$) and on the gate and oxide parameters (i.e., the gate workfunction $\phi_M$ and the oxide capacitance $C_{\text{ox}}$). The last term takes into account the variation of $V_t$ due to carrier confinement at the top interface. It depends on the effective electron mass $m_{\text{eff}}^*$ in the confinement direction [0 0 1] and on $t_{\text{si}}$, $k_B$, and $\hbar$ are Boltzmann’s and Planck’s constants, respectively. $q$ is the electronic charge. Given that $n_{\text{si}}^0 = \sqrt{N_{\text{C}} N_{\text{V}}} \exp(-E_{\text{gsi}}/2)$, the $V_t$ shift $\Delta V_t = V_t^{\text{SOI}} - V_t^{\text{SOT}}$ induced by the biaxial strain is thus given by:

$$\Delta V_t = -\left( \chi_{\text{si}} - \chi_{\text{Si}} \right) - \frac{k_B T}{2q} \ln \left( \frac{N_{\text{C}} N_{\text{V}}}{N_{\text{C}} N_{\text{V}}^0} \right)$$

$$+ \frac{\hbar^2 \pi^2}{8 q m_{\text{si}}^*/ \left( m_{\text{si}}^* + m_{\text{si}}^* \right)}$$

(2)

As the effective carrier masses hardly changes with biaxial strain [18–20], the second and third terms can be neglected (~8 mV and ~0.3 mV, respectively, at worst for $k_{\text{ge}} = 0.4$, i.e., less than 5% of the experimental $\Delta V_t$). Therefore, in FDSOI devices, $\Delta V_t$ can be directly linked to the conduction band offset $\Delta E_C = -\left( \chi_{\text{si}} - \chi_{\text{Si}} \right)$. Using the (1 0 0) strain tensor [11], it is expressed as

$$\Delta V_t = \Delta E_C = \Delta E_{C^2} = \Sigma_{\alpha} (\Sigma_{\alpha} + e_{\alpha}) + \Xi_{\alpha} e_{\alpha}$$

(3)

where $\Sigma_{\alpha}$ and $\Xi_{\alpha}$ are the dilatation and uniaxial deformation potential coefficients of the Herring’s theory [21], respectively.

The experimental $\Delta V_t$ values have been compared to this model in Fig. 3. The best fit was obtained with the values $\Xi_{\alpha}$ and $\Sigma_{\alpha}$ proposed by Kanda [13] and given in the inset of Fig. 3.

3.3. Gate leakage

The gate leakage current densities $J_g$ in unstrained and strained devices were compared in Fig. 4 as a function of the oxide field $E_{\text{ox}}$. In the trap-assisted-tunneling regime (TAT) [22,23], $J_g$ weakly depends on strain since it is rather controlled by the trap density in the oxide. In contrast, in the Fowler–Nordheim regime (Fig. 6, $\phi_b < q \cdot V_{\text{t}}$), $J_g$ was reduced at same $E_{\text{ox}}$ compared to $J_g^{\text{SOI}}$. This reduction is plotted in Fig. 5 versus stress level.

Considering that there is only one injection level, the lowest energy level $E_{\text{c}}$ [24,25], and that the effective barrier $\phi_b - E_{\text{c}}$ is almost constant in the FN regime, as proposed by Weinberg who considered a constant mean value for $E_{\text{c}}$ [24,25], a simple method, based on the FN classical expression, is then proposed to extract the barrier height $\phi_b$ (Fig. 6):

$$J_f = A \cdot E_{\text{ox}}^2 \cdot \exp \left( -\frac{B (\phi_b^{\text{FN}})^{3/2}}{E_{\text{ox}}} \right)$$

(4)

with

$$A = \frac{q^3 (m_{\text{c}}^*/m_{\text{c}}^*)^{1/2}}{8 \pi \hbar \phi_b^{\text{FN}}}$$

(5)

Fig. 3. Strain-induced variations of $V_t$ ($\Delta V_t = V_{\text{t}}^{\text{ex}} - V_{\text{t}}^{\text{ex}}$) and of barrier height $\phi_b$ ($\Delta \phi_b = \phi_b^{\text{ex}} - \phi_b^{\text{ex}}$) with respect to the stress in the (0 0 1) plane. Inset: potential deformation values found in the literature. Experimental data are in very good agreement with Kanda’s values.
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